Capturing Uncertainty in the Common Tactical/Environmental Picture

Airlie Conference Center
Warrenton, VA
Oct. 16-17, 2000

ONR Program Participants:

Ocean Modeling and Prediction
Ocean Acoustics
Physical Oceanography
Undersea Signal Processing
Sensing-Information Dominance

Capturing Uncertainty

Goals of the Workshop

- To communicate the scientific issues and the potential benefits of the DRI to the scientific community

- To identify the priority areas of "discovery" research that will lead to a new level of understanding in this area

- To identify the incremental steps for improving present methodologies

- To build a common vocabulary and define an inter-disciplinary team approach to this research

Capturing Uncertainty

Overall Objective of the DRI

- Characterize, calculate, and transfer uncertainty in the environment to calculations of acoustic fields and to the subsequent use of the acoustic fields in performance prediction, in estimating and displaying the state of targets, and in other Navy relevant applications.

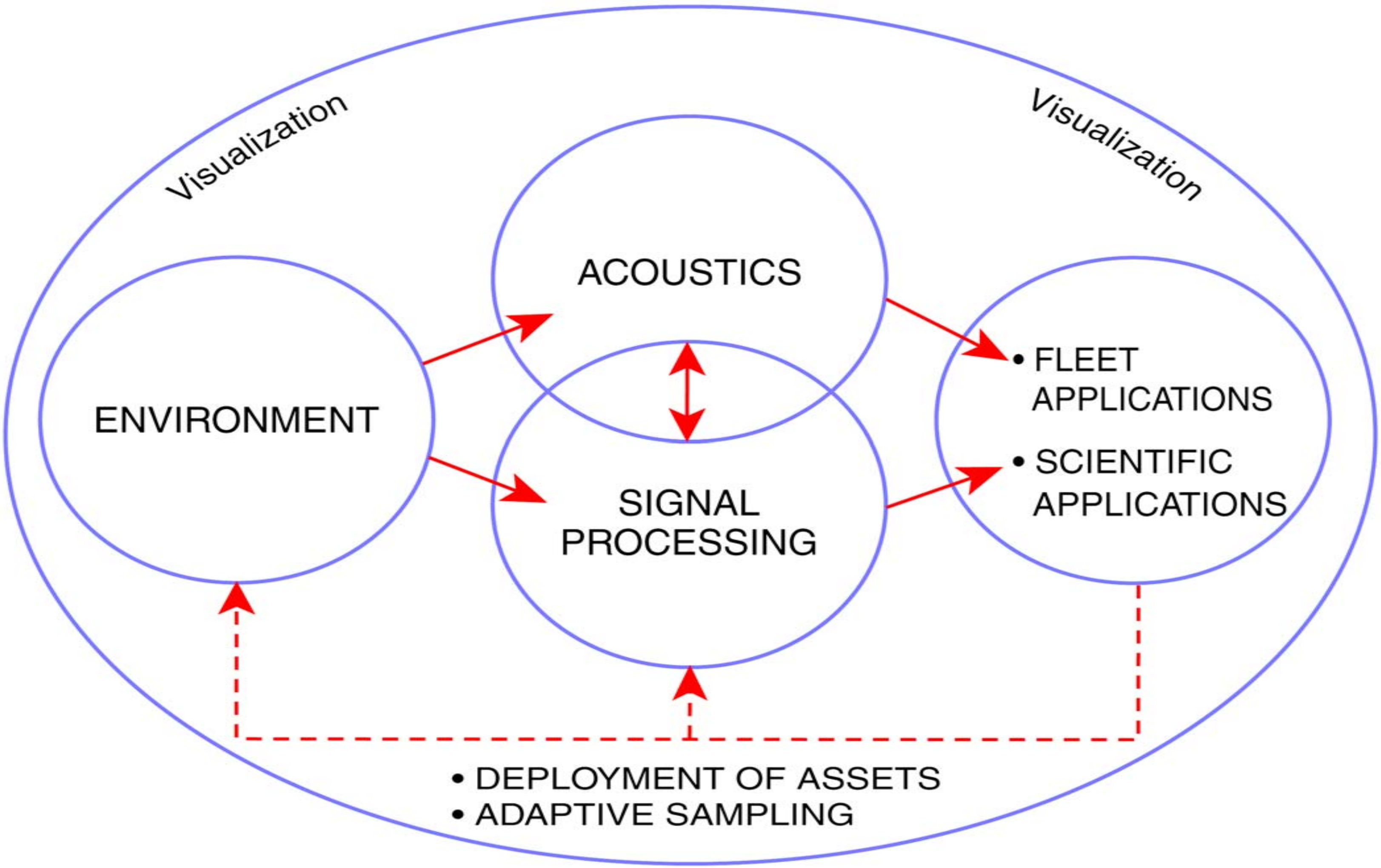
Capturing Uncertainty

Specific Goals of the DRI

- Develop a formalism for quantifying uncertainty
- Develop methods for transferring uncertainty from one field to another or one calculation to another calculation
- Develop techniques for conveying this information to users in a meaningful way

Capturing Uncertainty

CAPTURING AND TRANSFERRING UNCERTAINTY



Working Definition of Uncertainty

E = the estimated value of some quantity
(measured, predicted, calculated)

A = the actual value (unknown true nature)

U = E-A

The uncertainty in E can be represented by the probability distribution function of U, where we recognize that this distribution need not be normal, have a 0 mean, or be unimodal.

For the fleet, this definition includes, for example, environmental variability, errors in calculation, measurement error, etc.

Capturing Uncertainty

Some Specifics and Caveats Bounding the DRI

- environment doesn’t always introduce uncertainty into the use of acoustics, but we wish to focus on where and when it does
- passive case as a starting point but also active
- shallow water as a topical area of concern
- lower frequencies, ASW type, below several kHz
- volume (primarily) but with consideration of interactions with the bottom

Capturing Uncertainty

Some Specifics and Caveats Bounding the DRI

- Need to bound the huge range of scales of environmental structures and environmental processes that affect performance
  - seconds over meters for sensor engineering issues
  - hours over kilometer(s) for sensor and multi-platform system performance (as a starting point)

- noise, surface processes, and shipping noise contribute to uncertainty, may be knowable, but the details of predicting these processes are not the highest priority for this DRI

Capturing Uncertainty

Charge to the Workshop Experts

- Discuss the concepts, factor in the state-of-the-science based on your experience
- Formulate the research questions to achieve the specific goals of the DRI
- Identify research areas that enable discovery and those that facilitate incremental improvement of present methods
- Summarize findings from working groups

Capturing Uncertainty

Format of the Workshop

- Presentations from the working group on an illustrative problem
- Discussion of the research issues raised by considering this problem
- Breakout into working groups to give full consideration to the scientific issues
  - working members encouraged to show viewgraphs briefly and when relevant to the conversation
- Plenary session to build a consensus and foster an interdisciplinary approach

Working Groups

Charges

- What are the research challenges in quantifying, propagating, and utilizing uncertainty in the Navy's use of the environment, acoustics, and tactical decision aids?

- What are the far reaching research foci that need to be attempted in order to move towards an ultimate quantification and use of uncertainty (the 6.1 research foci)?

- What can be done by fully utilizing today's research potential towards an immediate use of quantified uncertainty (the 6.2 research foci)?

Working Group Assignments

A. East Room
B. Studio Room
C. Foxes Den
D. Garden Room

Working Group Assignments

A	B	C	D
<u>Abbot</u>	<u>Lynch</u>	<u>Gawarkiewicz</u>	<u>Colosi</u>
Lozier	Levine	Bogden	Robinson
Finette	Pang	Henyey	Miyamoto
Bartek	Goff	Krolik	Syvitski
Cable	Gauss	Gough	McCammon
Egbert	Kirwan	Miller	Moore
Gordon	Titley	Smith	Hodgkiss
Lermusiaux	Allard	Abraham	Kelley
Zittel	Zarnich	Cuff	Godin
Incze	Van Gurley	Hart	Raff
			Streit

ONR program officers rotate between groups

Capturing Uncertainty Working Group

- **Expectations:**
  - Coordinated presentations at the expert workshop;
  - Other material that helps support development of the DRI such as white papers, sample calculations, etc.
  - Integrated report on the state-of-the-science and challenges inherent in making progress in this area (an expansion of the coordinated presentations.

- **Procedure**
  - Briefing on ONR's interests and intentions in this area
  - Discuss possible approaches to illustrate the DRI concept*
  - Engage in developing the "illustration"*
  - Expert workshop in October '00 (your feedback solicited)
  - Integrated report to ONR in October '00 ("   ")

** Submit small proposal for support*

Capturing Uncertainty Working Group

- **What do we mean by "uncertainty"?**

- By uncertainty we mean the environmental variability that is knowable and that we can simulate, the environmental variability that is knowable but that we can not simulate, the environmental variability that is not knowable, and the error inherent in representations, observations, and calculations of the environmental field, acoustic field, and target estimation.

- **What do we mean by capturing uncertainty?**

- Characterizing, calculating, quantifying, and representing.

Capturing Uncertainty Working Group

- **Approaches that have been used in the past for capturing uncertainty:**

- Monte Carlo
- Propagation of Moments
- Bayesian Inference
- other??

- **How do we excite the exploration of optimum approach(es)?**

Capturing Uncertainty Working Group

Approaches we have considered for illustrating the concept of the DRI:

• Having a pilot group work through a realistic problem that is based on a recent and intensive set of observations:

Example: Shelf-Break Primer as a observational basis where by modeling with data assimilation has been conducted, internal wave processes have been model, the acoustic field has been calculated. The challenge: how would you take these products and quantify the uncertainty and then propagate this measure through to a target state-estimation?

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- **Approaches we have considered for illustrating the concept of the DRI:**

- Alternatively: have a pilot group create a synthetic problem where a know amount of uncertainty is added and the goal is to attempt to recover/keep/quantify that uncertainty at each step in the path from environmental field representation to target state estimation.

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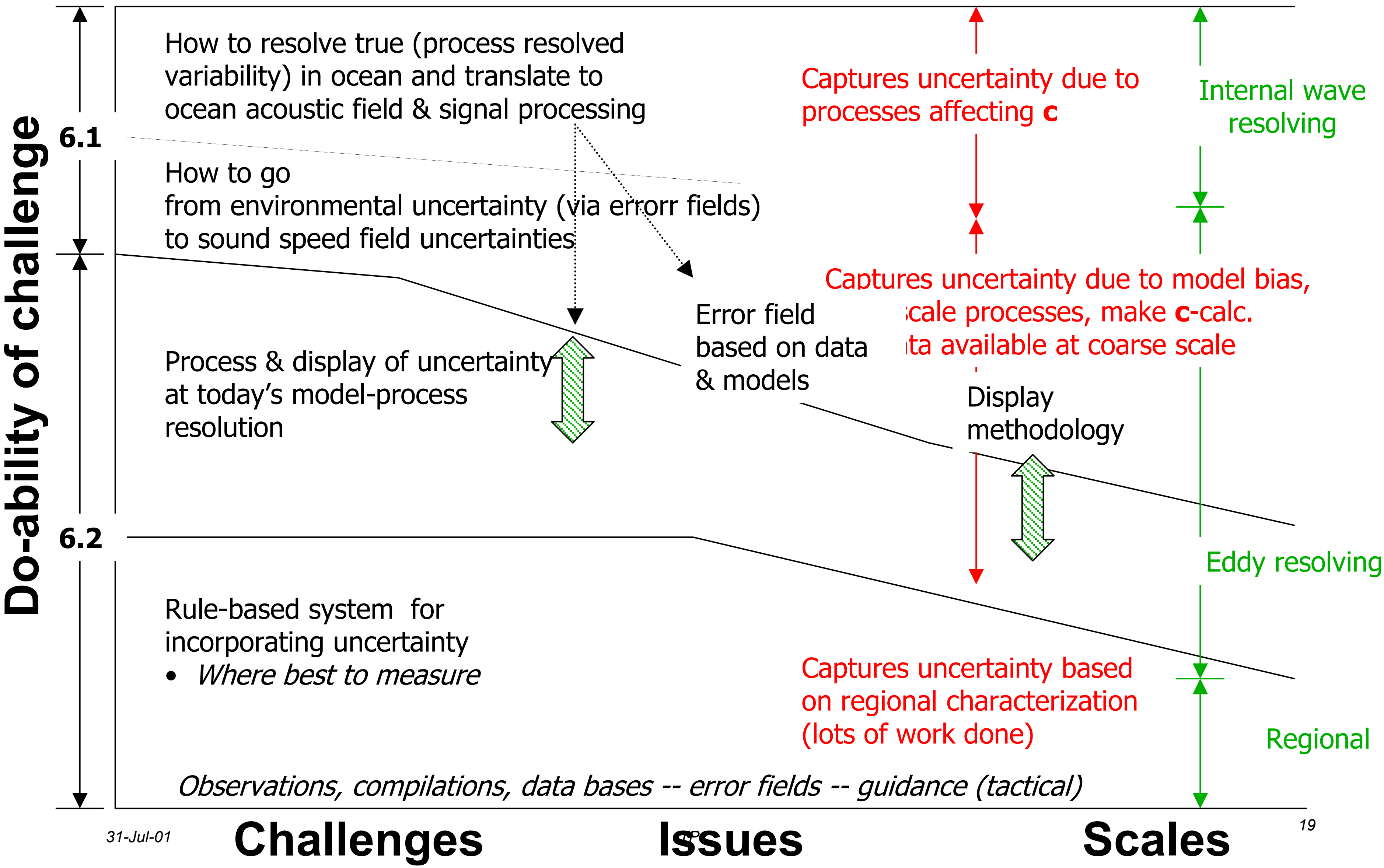
•**Consider also:**

• How to determine impact on the systems?

Passive detection
Active detection
Arrays

Translate Environmental Uncertainty to Meaningful Acoustic Fields



Our view of the current state and the potential

- **Present-day nowcast models resolve processes at the grid resolution and above and treat sub-grid scale processes through parameterizations.**
  - **The Nowcast process, through data assimilation, provides an estimation of the difference between the modeled state of the environment and the measured state of the environment. Data assimilation provides an estimation of the errors in the data and the uncertainty of the model results. This captures the grid scale levels of uncertainty.**
  - **These models do not include the stochastic component of the environment and the sub-grid scale parameterizations are not adequate representations of uncertainty due to processes such as internal wave fields.**

Our view of the current state and the potential

- Challenge: how well do the present nowcast models and data assimilation systems capture environmental uncertainty?

- Challenge: how can representations of the acoustic field utilize the measures of uncertainty from the nowcast process

- Challenge: how well could the environmental uncertainty be captured in the future?

Our view of the current state and the potential

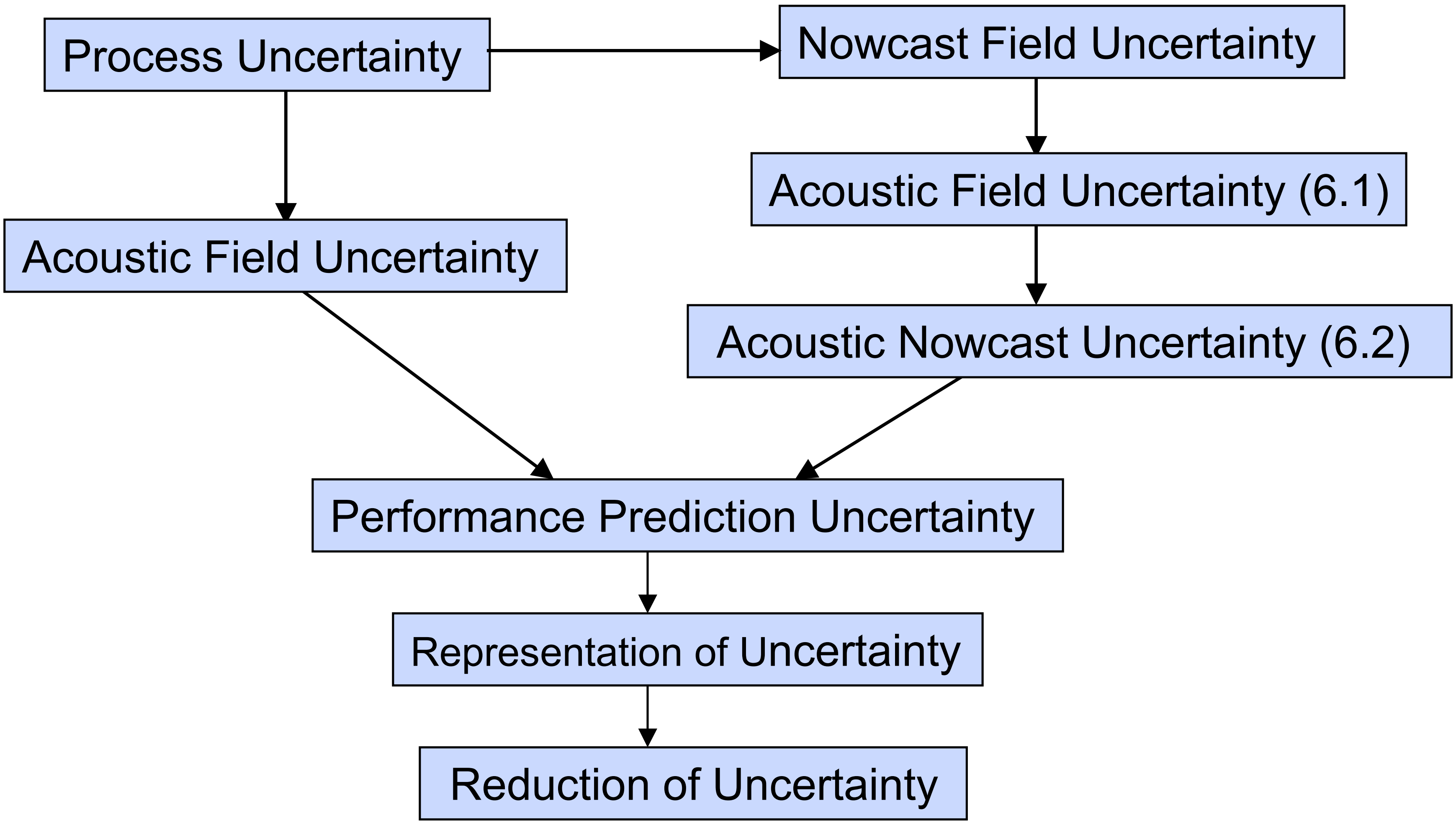
- Uncertainty in the sound speed field causes uncertainty in the estimated acoustic field

- Uncertainty in the acoustic field causes uncertainty in target state estimation.

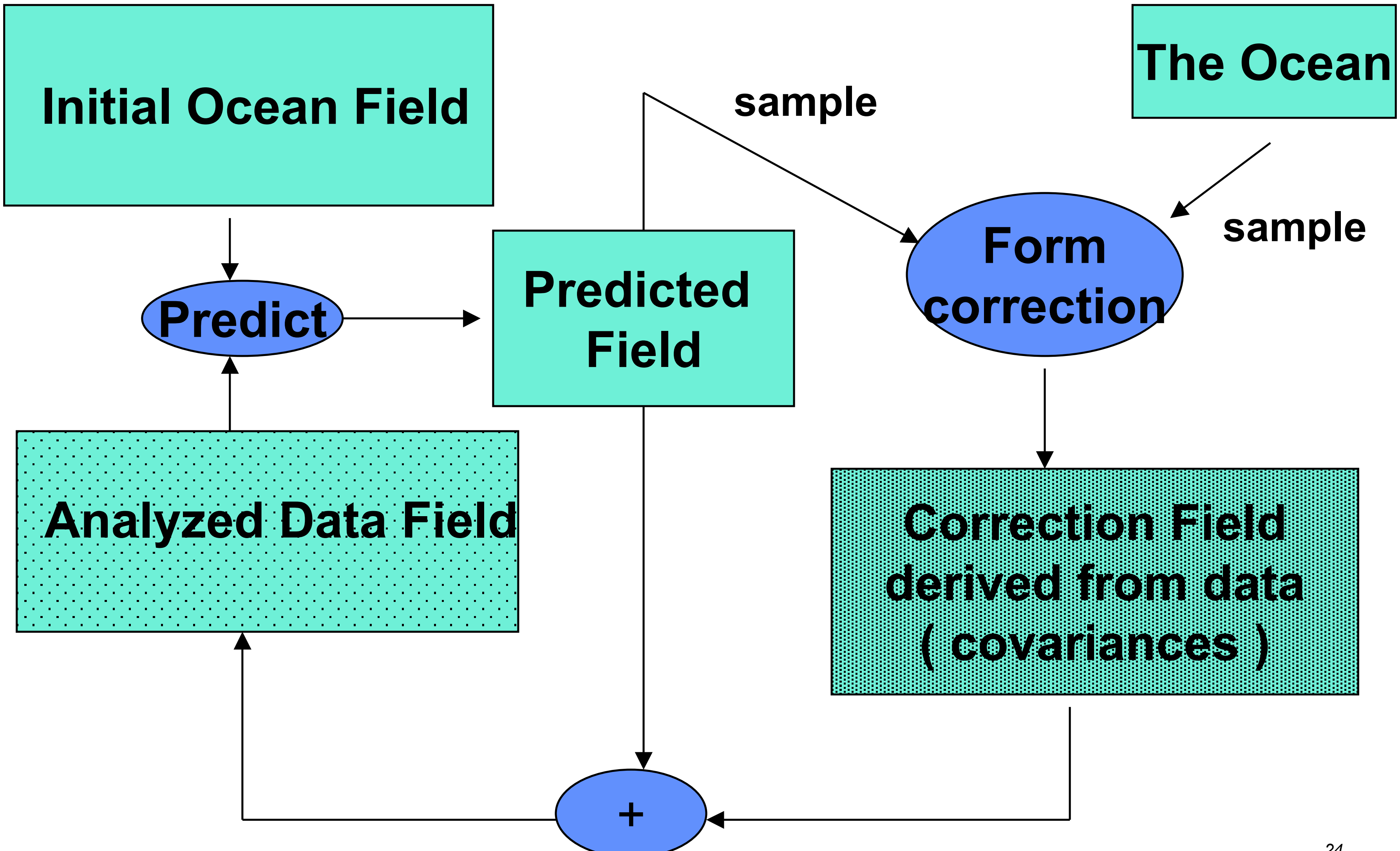
- Representing the multi-dimensional USW target state space is difficult, representing the added dimensions of uncertainty in a meaningful way is still an area of research.
  - Challenge: how to represent the “fog” of uncertainty while maintaining a clear view of the most likely state

- Once uncertainty is known, resources may be allocated to reduce it (resources means data collection, sensor location,etc.)
  - Challenge: how to build an automated, optimizing, “expert system”

Capturing Uncertainty



Start with Navy paradigm of Nowcast



NOWCAST PATH

Practical Data Assimilation

NOWCAST PATH

Model
w^f

Data
w^o

Errors:
- Initial conditions
- boundary conditions
- Surface forcing
- Parameterizations

Errors:
- Measurement
- Processing
- Aliasing
- Missing Data

Forecast Error Covariance → P^f_{nxn}

K=gain matrix
H=interpolation matrix

Observation Error Covariance → R_{pxp}

$$K = P^f H^T (H P^f H^T + R)^{-1}$$

$$w^a = w^f + K(w^o - Hw^f)$$

ANALYSIS w^a

What can be utilized

A

Ocean Nowcast Field

Data Field

B

Covariance Matrix

D

Acoustic Field using A & B

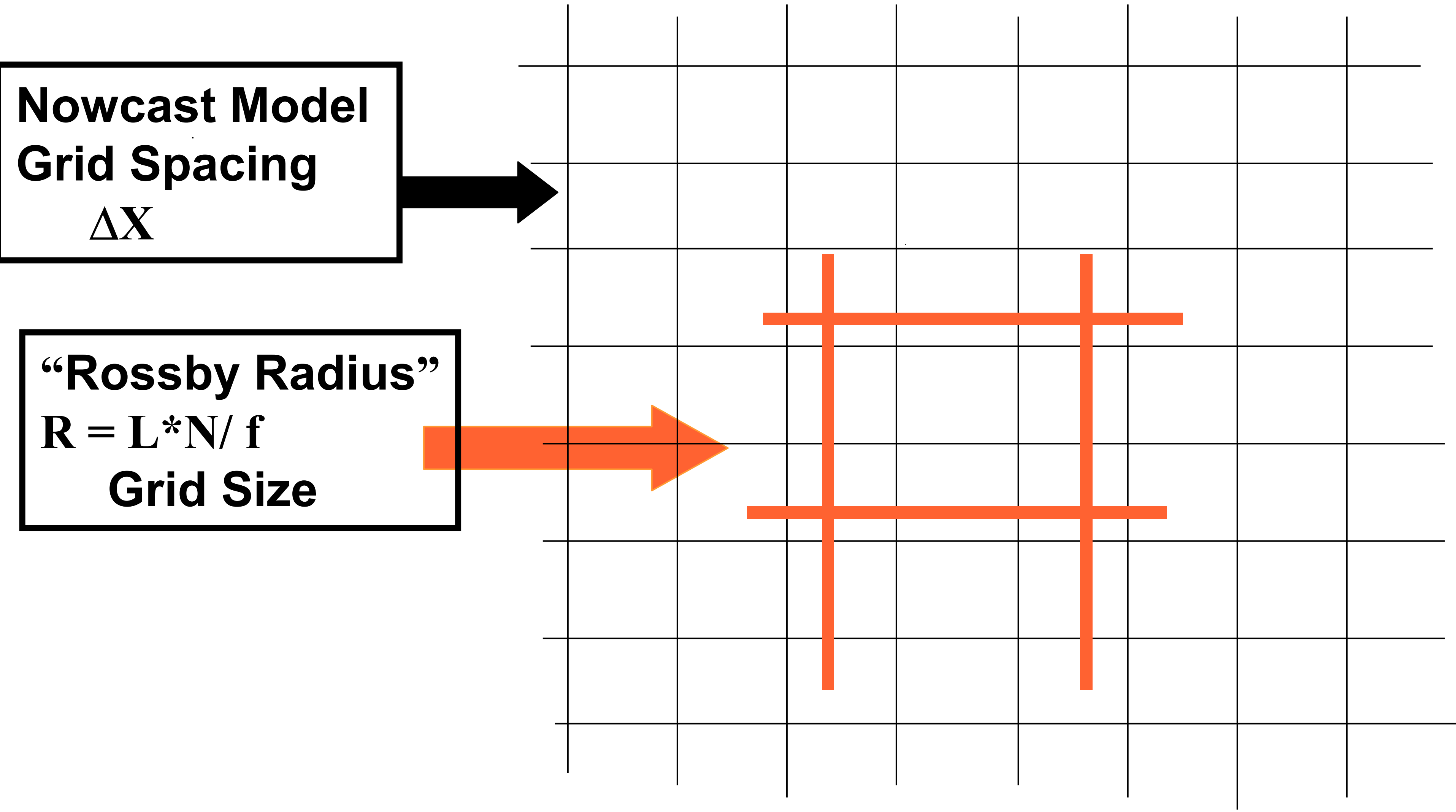
6.1 science need

Signal Processing using D

6.1 science need

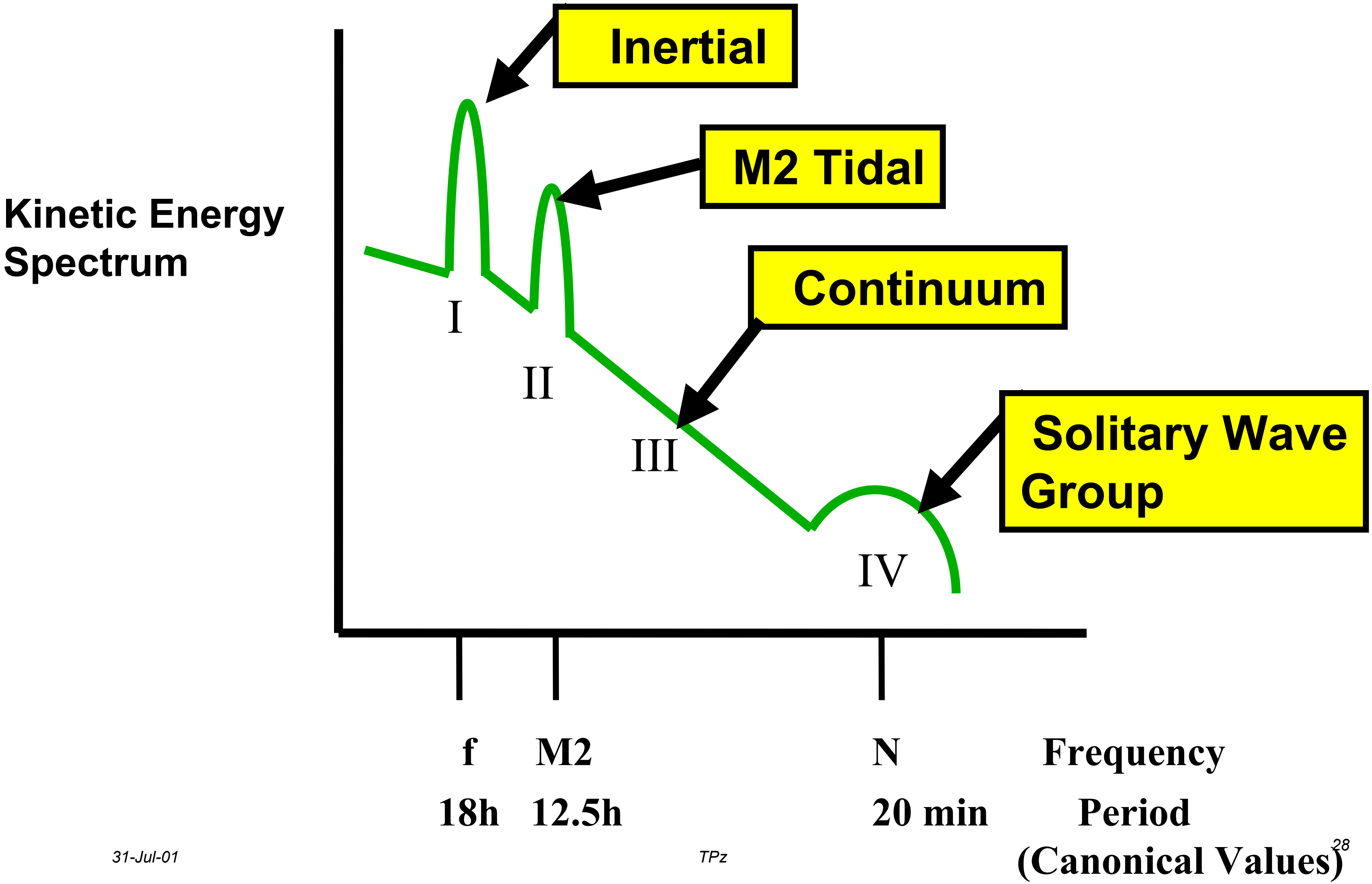
Sensor Performance Tactical Information

Nowcast Modeling Grid Size Versus Rossby Radius Grid Size



Note: Physics Uncertainty Typically of Order and Less than R (Fronts , Eddies, Internal Waves, Turbulence)

Internal Wave Components



State of Knowledge of IW Uncertainty

Band	Process	Shelf	Slope	Open Ocean	Sources of Uncertainty	SVP Impact On tactical scales (< 25km)
I	Inertial	??	??	L ~50 km	Random Initial Conditions, evolution process not well known	Surface Duct erosion
II	M2 Tidal	L~10km	L ~75km	L ~150km	Generation Model	Surface duct, SVP Dilation/ compression
III	Continuum	L ~ 100m -10km	L ~ 100m-75km	L ~ 100m- 150km ** Upper Ocean	Stochastic process; Issue of degree of groupiness, Gaussianity, isotropy; Generation unknown	Vertical/ horizontal randomization
IV	"Solitary" Waves	λ ~ 200m n ~ 2-20	??	λ ~ 1 km n ~ 2,3 to ??	Quasi Stochastic/ Chaotic; Generation and decay unknown	Vertical/ horizontal corrugation

Uncertainty Virtually Unknown
No covariance models exist.
Modeling not well developed,
very limited data.

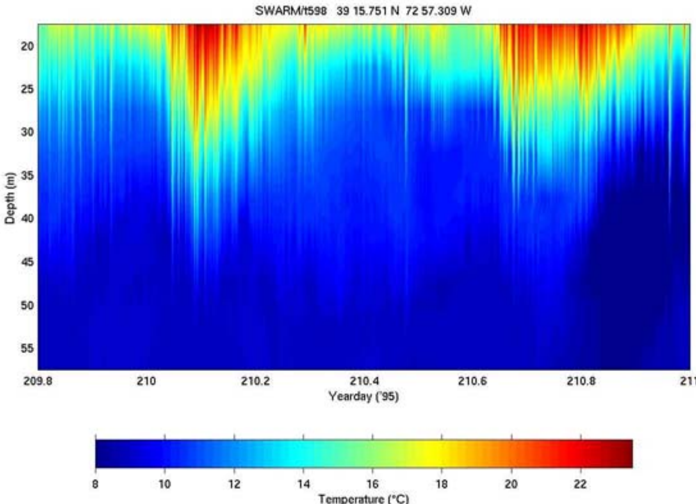
Uncertainty Moderately Well Known
Covariance models exist.

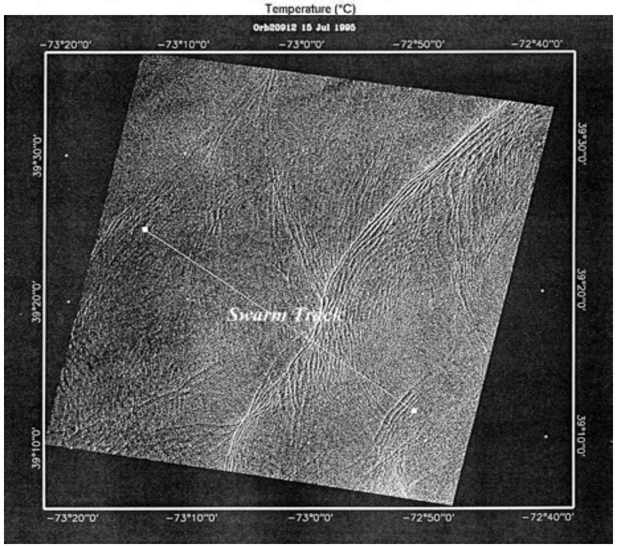
Uncertainty Modeling Limited
Covariance Models Under Development.
Several competing hypotheses,
some data, but limited in space and time.
** Refers to upper ocean continuum case being in "yellow" category

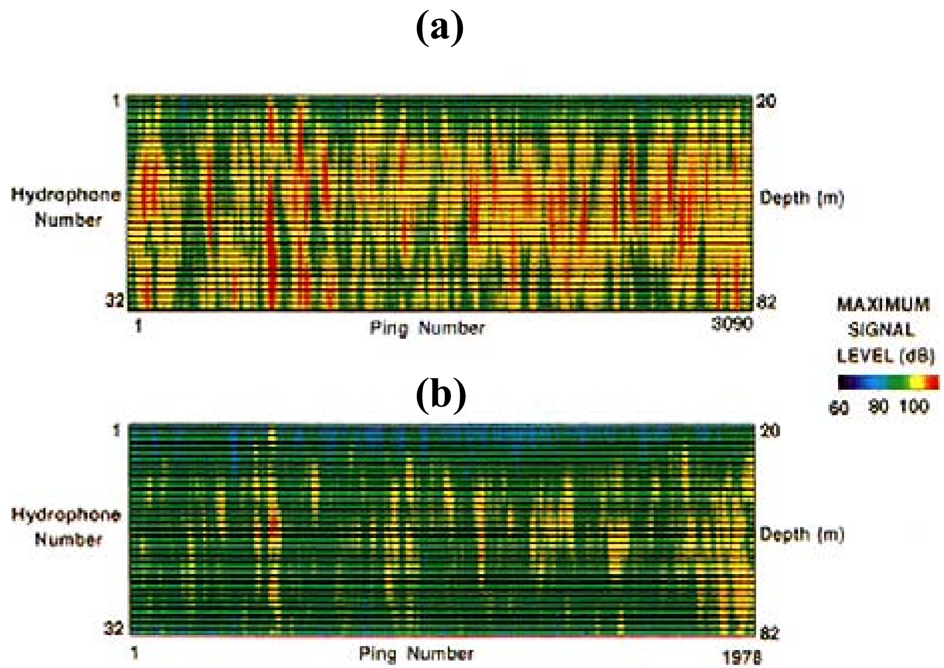
TPz

L = Horizontal Scale, λ = wavelength, n= number of waves in group

Ocean Variability → Acoustic variability







Maximum Amplitude Versus Depth over 8.4 hours for (a) 224 Hz and (b) 400 Hz. Note 30 dB variation

Acoustic Variability from Internal Solitary Waves (SWARM,1995)

The Challenge for the tactical acoustics need:

- Environmental uncertainty and the resultant uncertainty of the sound speed field makes the predication of acoustic wave propagation a difficult problem.

- How can we model uncertainty in the acoustic field - using the uncertainty from these environmental processes - in ways that will be useful for state estimation (signal processing and data fusion)?

Acoustic variability due to processes

PROCESS PATH

Simulate the ocean-process with appropriate process model

Create multiple model realizations to estimate sound-speed moments

Calculation of acoustic field from source to receiver

Establish the PDF or moments of the process

Solve the prop. eqns for PDF or moments of acoustic field

Monte-Carlo ensembles or propagation-of-moments techniques

Estimates of the moments of the acoustic field

What the operational Navy does now

Either a climatalogical or snapshot ocean

Deterministic View of the Acoustic Field

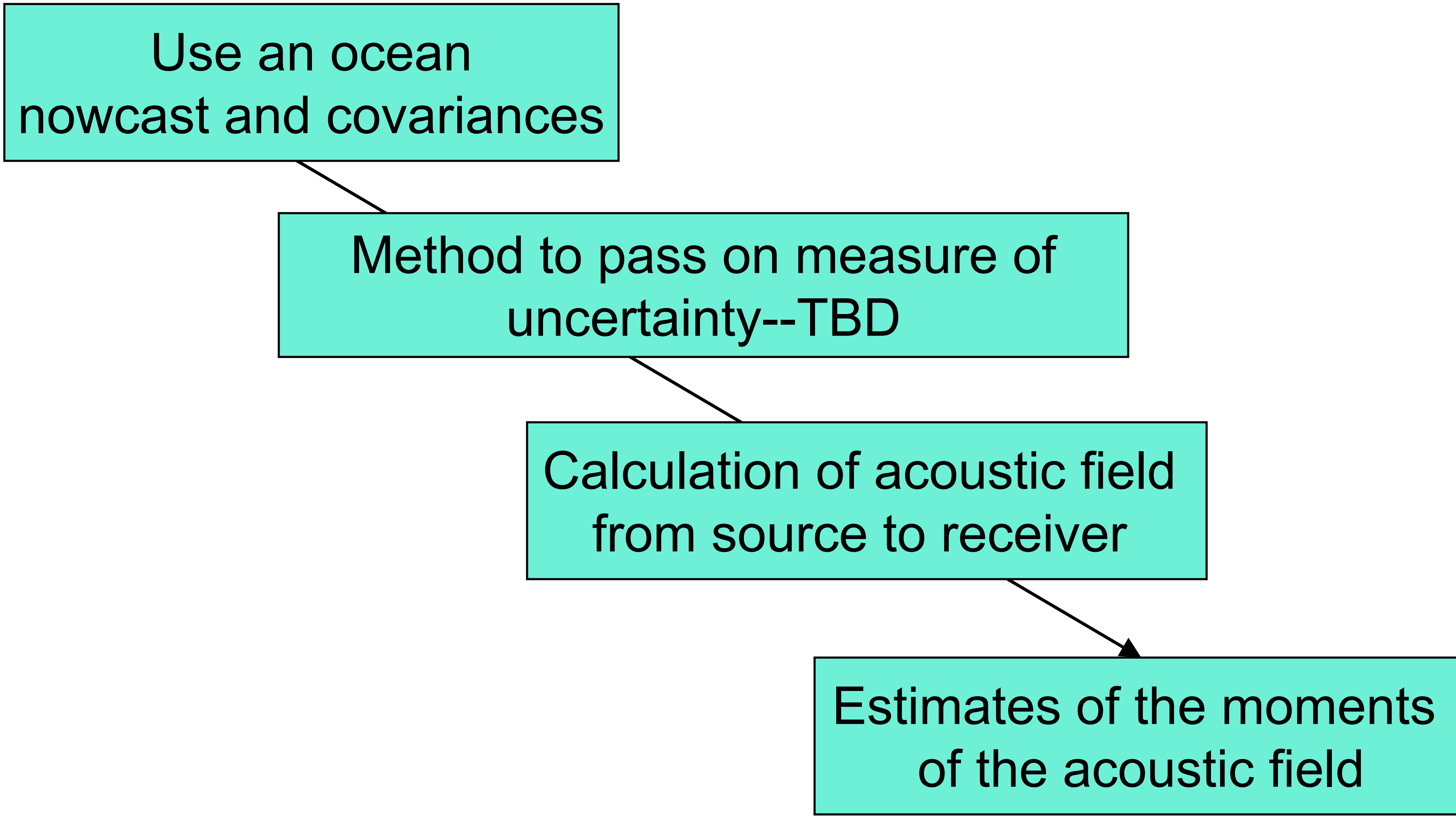
Complex Pressure Field across an Array

through Beam-Forming or Matched-Field Processing

Estimates of Sources in the Field of the Array

Potential elements of what could be done, given the current knowledge

NOWCAST PATH



What can we do now?

Two parallel pathways:

(2) Nowcast Uncertainty: exploit the estimates of uncertainty from the existing ocean Nowcast methods to provide estimates of uncertainty in the acoustic field and onward

- **develop an acoustic Nowcast process: use the covariances produced in the ocean Nowcast processes to get sound speed covariances / calculate the Nowcast acoustic field and the resultant uncertainty in the acoustic field**
- **Make an acoustic Nowcast process using optimal propagation methods to capture the uncertainty**
- **develop statistical signal processing algorithms to use the uncertainty**
- **further develop representations of the uncertainty in the acoustic field suitable for specific tactical products**

What can we do given an investment in basic research?

Two parallel pathways:

(1) Process Uncertainty: find a means to measure, model, and calculate the stochastic components of ocean processes into the acoustic field and onward, beginning with internal waves.

- **develop a statistical representation of uncertainty due to internal waves in the environmental field / use this to calculate a statistical representation of uncertainty due to internal waves in the acoustic field**
- **determine optimal propagation methods (propagation of moments, Monte-Carlo, other) within suitable regimes to transfer the uncertainty to the acoustic field**
- **further develop representations of the uncertainty in the acoustic field suitable for specific tactical products**

Currently Funded: Bayesian State Estimation

Likelihood Function

$$L(y|x) = \Pr\{Y = y | X = x\} \; for \; x \in S$$

$Y =$ Observation

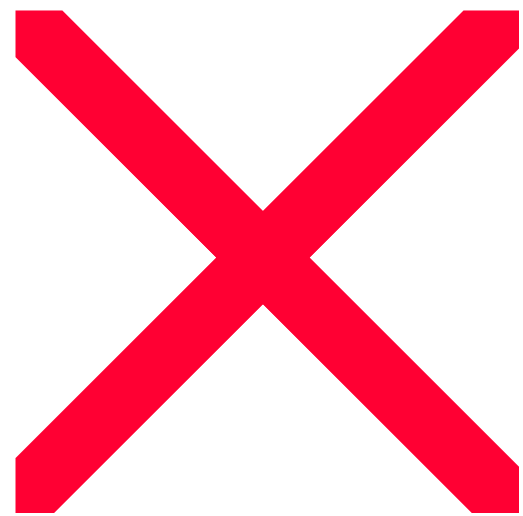
$X =$ Target State

Bayes Theorem

$$p(x|y) = \frac{L(y|x)\, p(x)}{\int L(y|x)\, p(x)\, dx}$$

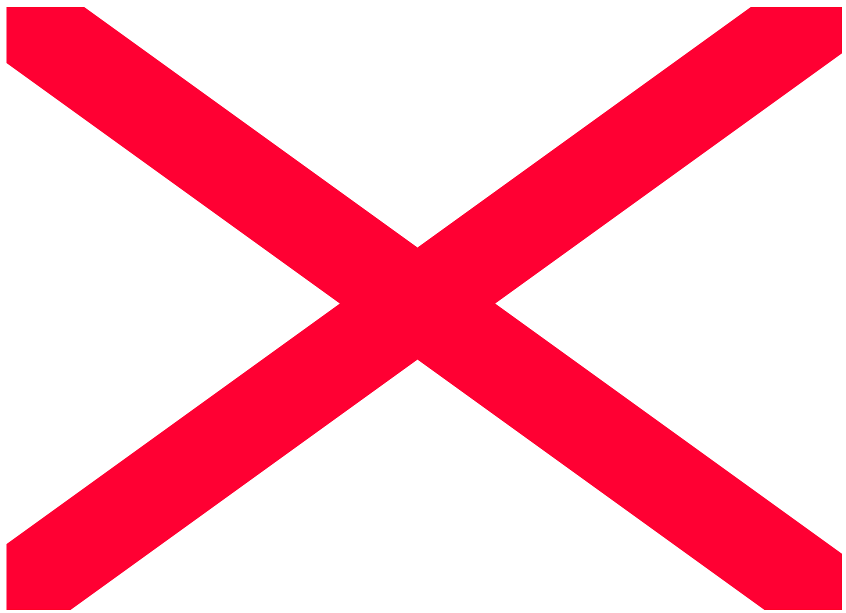
$$p(x|y) = C^{-1} L(y|x)\, p(x)$$

Introduce Uncertainty



Combined Acoustic Propagation and Sensor Beam Pattern Likelihood Function (sensor at (70,0)

Representation
(IMAT Display)



Tactical Guidance

Uncertainty of system performance.

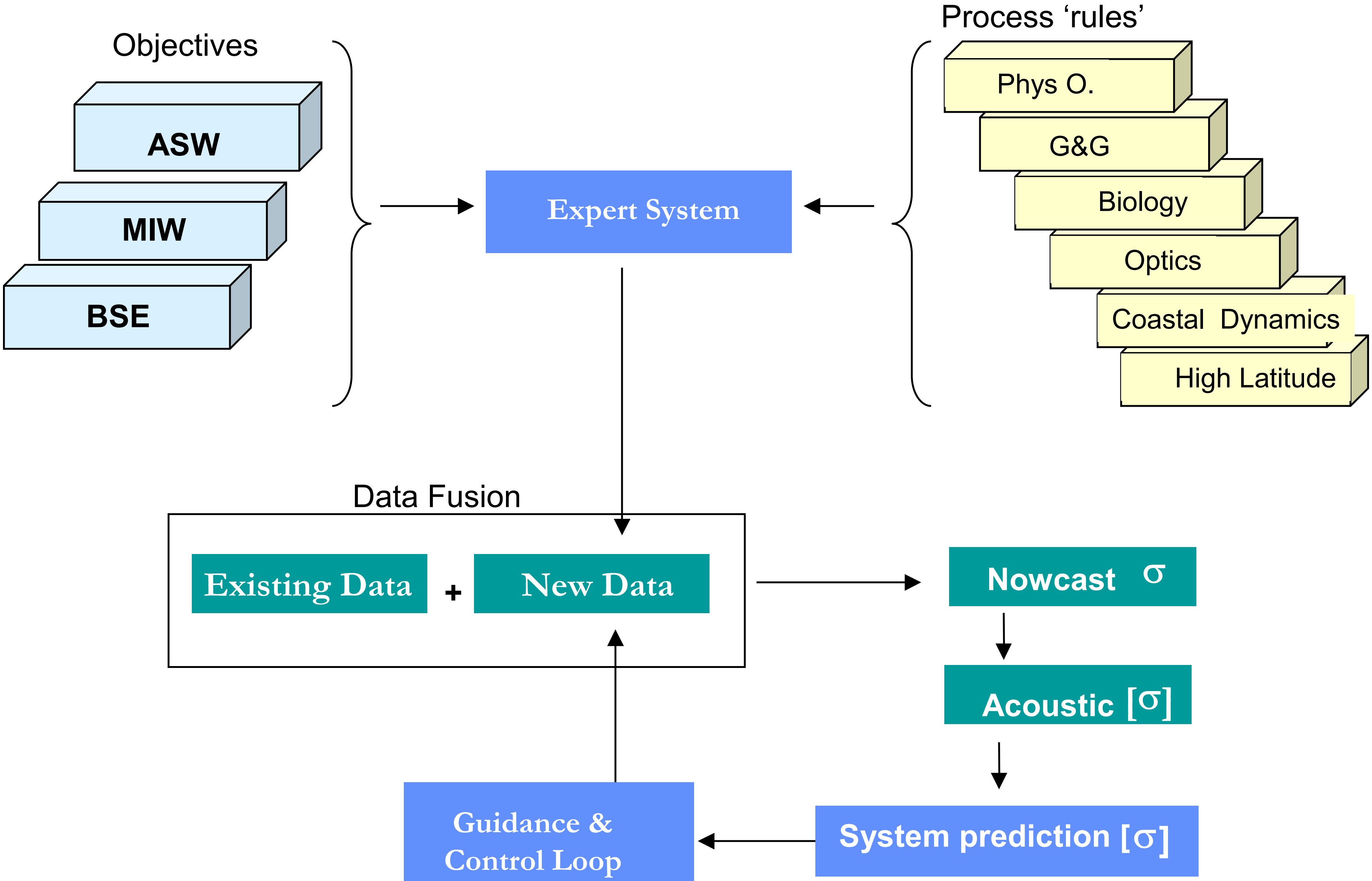
Environmental σ → Acoustic Field σ → System σ

- **Display Uncertainty of system performance (e.g. target localization) to the operator**

- **Develop tools to reduce this uncertainty, via**
  - **Intelligent data collection**
  - **Signal Processing algorithms**

- **Exploit uncertainty**

Tactical Guidance



DRI Proposal: Why Now?

- Evolution of numerical, statistical, and process understanding makes this research possible now whereas it was not previously.
- Note that it will take each research element to proceed in-step in order to progress in this area,
- Present efforts have created a core group of acoustic-oceanographers-signal processors. Now there is a need to bring in additional expertise in statistics, data assimilation community, signal processing, tomography
- Navy need is critical.
- Leverage field effort